Current in situ sensor platforms

DRIFTER

Cheap and easily deployed, power in numbers

Cost: $500-6,000
Depth: 0-100m
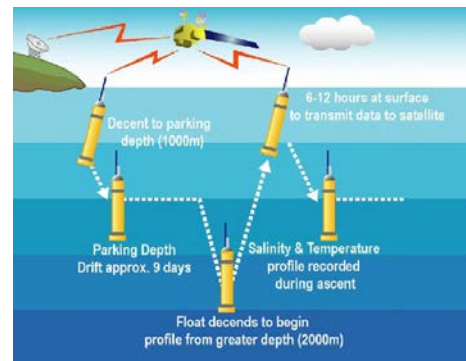Motion: Lagrangian drift

Ex: Sonobuoys, Sofar Spotter

FLOAT (profiler)

Ability to change depth by adjusting buoyancy or crawling a mooring line

Cost: $20,000-100,000
Depth: 100-6000m
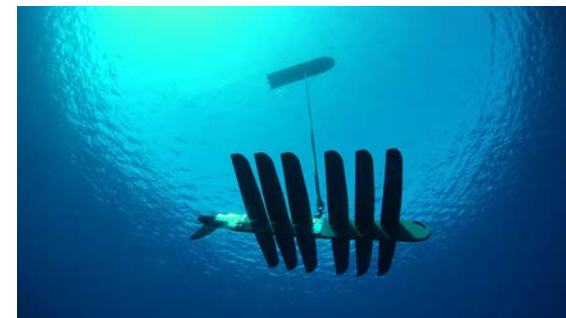Motion: Moored or drifting

Ex: Argo program

AUTONOMOUS

Self-powered, steerable, long activity cycle

Cost: $200,000-10,000,000
Depth: 200-1,000m though some have reached 6000m
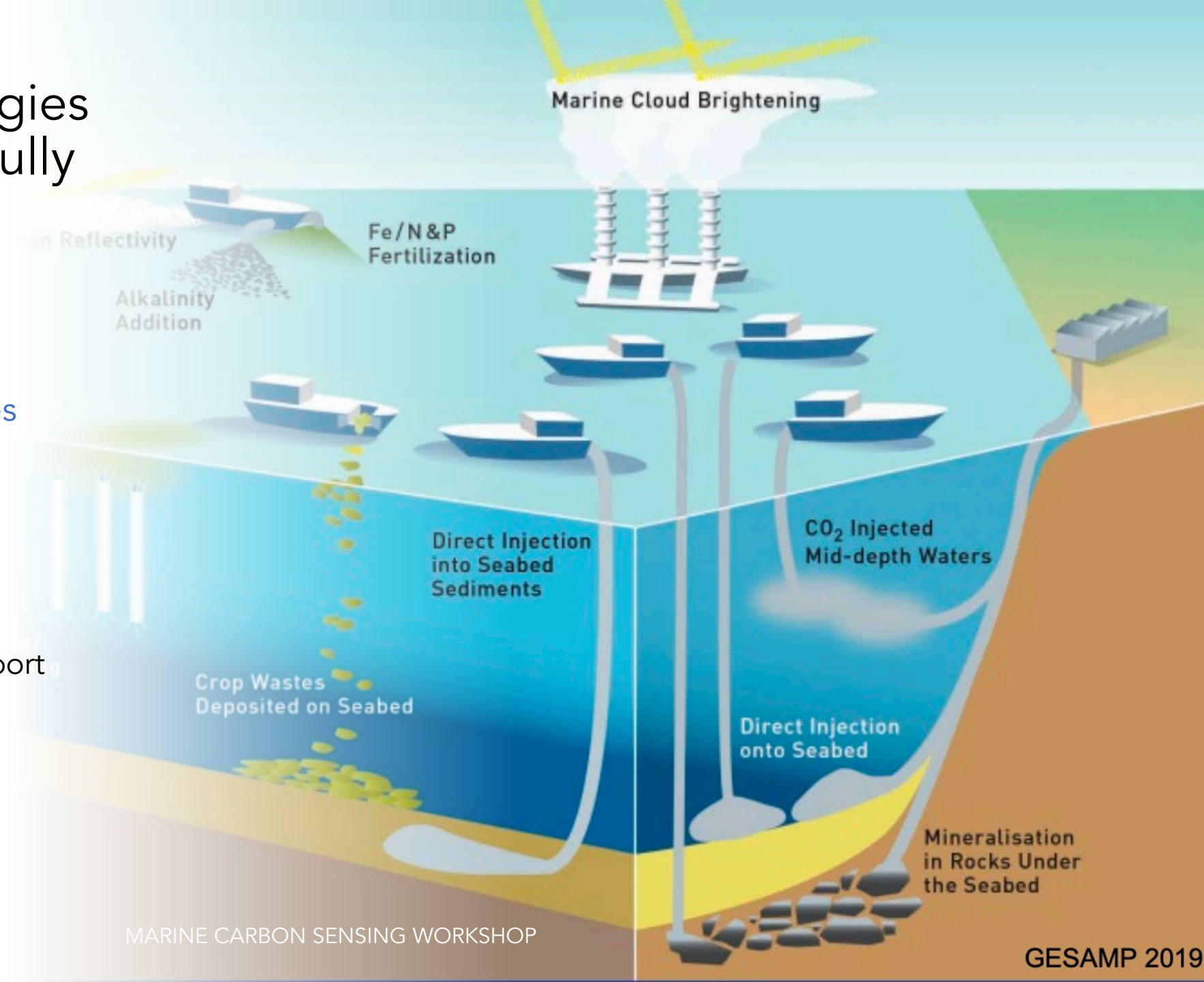Motion: Pseudo-active

Ex: Wave Glider

Platform technologies critical to successfully measuring and reporting of CO_2

- **Measurement Challenges**
  - Spatial
    - $10^{-2} \rightarrow 10^2$ km
  - Temporal
    - $10^{-3} \rightarrow 10^2$ years
- **Platform Challenges**
  - Environment
  - Efficiency/ Cost of Transport
    - Range
  - Energy generation
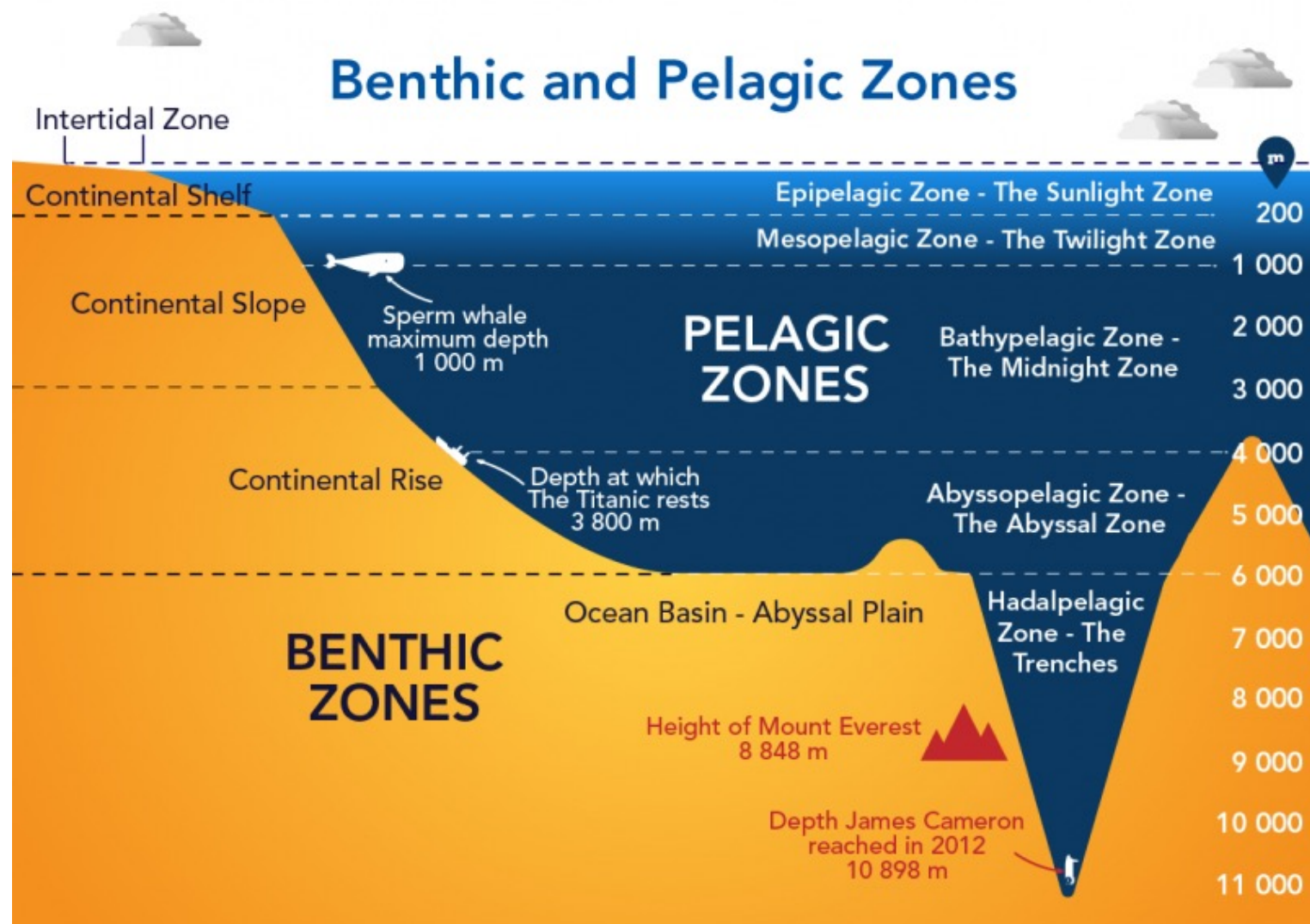   - Duration
  - Robustness
  - Economics

Marine Cloud Brightening

Ocean Reflectivity

Fe/N&P Fertilization

Alkalinity Addition

Direct Injection into Seabed Sediments

CO_2 Injected Mid-depth Waters

Crop Wastes Deposited on Seabed

Direct Injection onto Seabed

Mineralisation in Rocks Under the Seabed

GESAMP 2019

Ability to actively/passively monitor carbon levels in **all ocean zones** will require new solutions in the underwater platform design space

Opportunity to go beyond traditional platform design and take inspiration from biology: manmade underwater vehicles have had ~250 years to evolve, biology… millions of years

DIVERSITY OF DESIGN: 35,000+ species of known fishes occupying all oceanic zones presents incredible morphological diversity

Mother nature offers inspiration


Benthic and Pelagic Zones

Biological Propulsion: Diversity of Design & Inspiration

- **Biology has evolved solutions to inhabit all oceanic zones**
  - ➢ Offers the potential for game changing solutions for autonomous platform designs that form the framework to quantifying carbon in the ocean
  - ➢ Must be clear on what aspects of their solution are critical to success
    - ➢ SPATIAL/TEMPORAL//ENERGETICS/COST/ETC CONSTRAINTS
  - ➢ Idea is not to mimic biology but be inspired

- **Fishes are not pressure vessels**
  - ➢ IDEA OF DEPTH AGNOSTIC SYSTEMS
    - ➢ Removing pressure vessel design through soft, solid-state components opens up deep ocean zones for MRV
  - ➢ ECONOMICS OF SOFT SYSTEMS
    - ➢ Cost less than traditional *metal-foam* UUV designs

Cost of Transport

Quantifying Energy Efficiency

Cost of Transport (i.e., energy efficiency): varies with speed and species
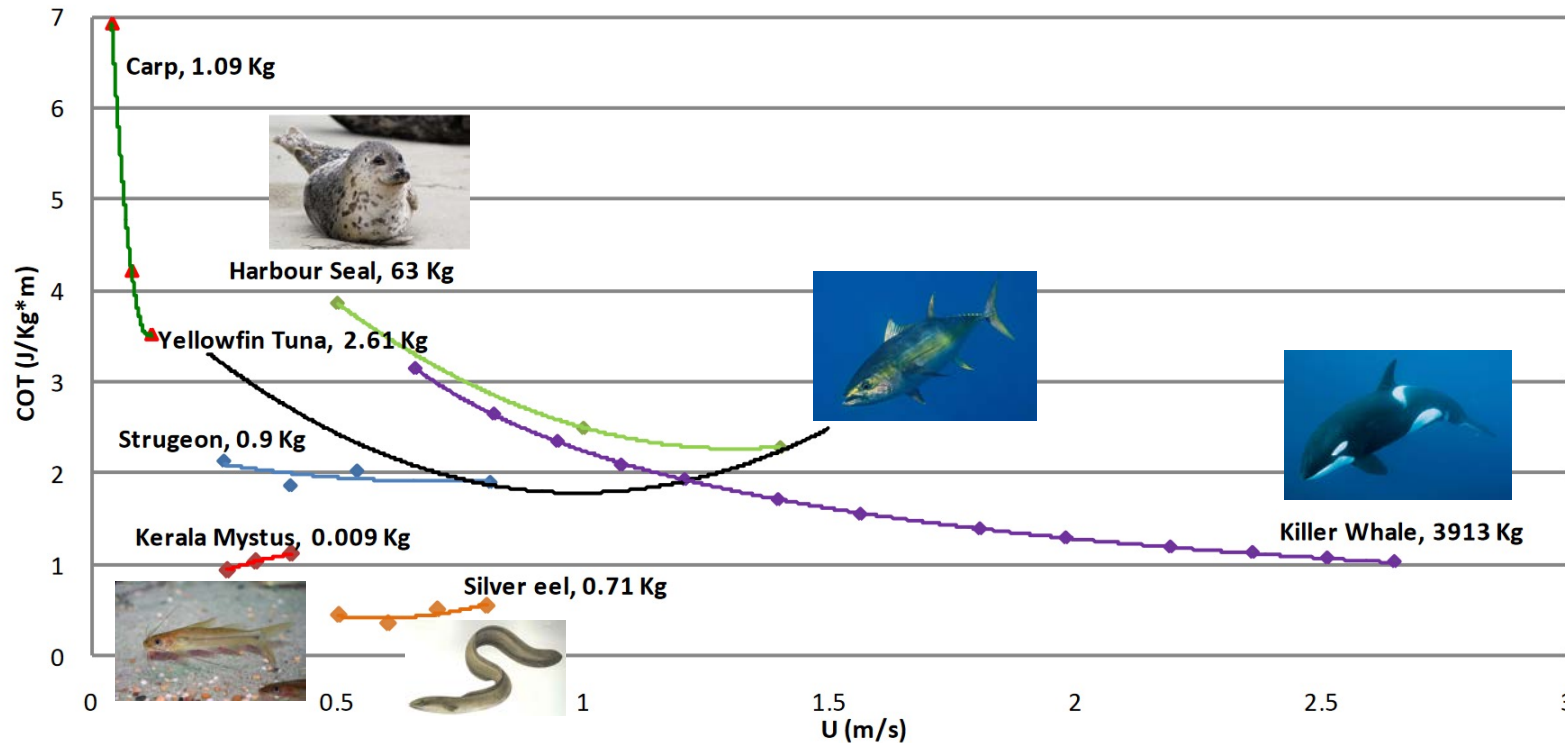
- Active metabolic rate of fish is analogous to electrical power consumption of platform ==> cost of transport scaled by body mass (J/kg/m) **allows biology-robot comparison directly**
- CoT is a key metric to quantify
- Understand recharging requirements for long duration sensing runs
  - *Charging stations (analogous to cleaning stations of Manta Rays)*

(Phillips et al., 2012, Further Advances in Unmanned Marine Vehicles, edited by G.N. Roberts and R. Sutton ISBN: 978-1-84919-479-2)

Pressure drag

Lift-based propulsion

Acceleration reaction

Biological Propulsion:
Diversity of Design & Inspiration

Lift-based propulsion

GhostSwimmer Autonomous Undersea Vehicle (AUV) by Boston Engineering
- Tuna-inspired
- Maximum depth: 100 m
- Endurance: 14 hrs
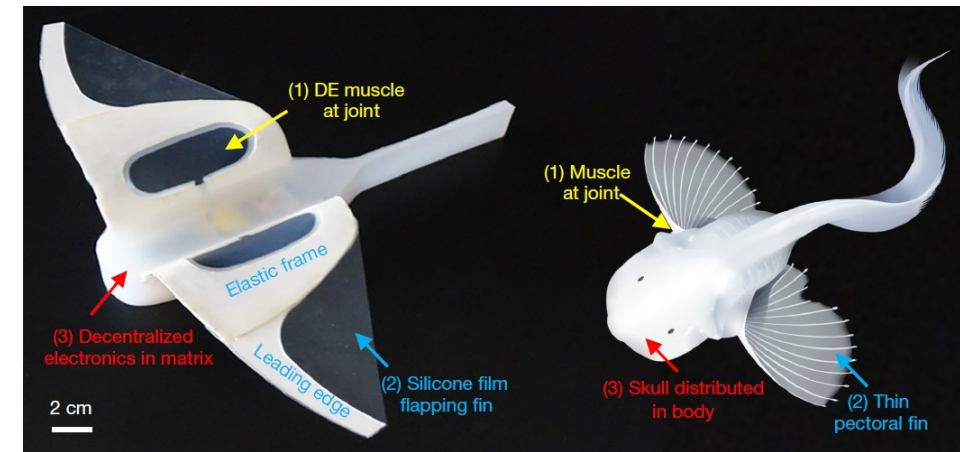
Soft robot (left) inspired by snailfish (right)
- Swam at depth of 10,900 m in the Mariana Trench
- Actuated by dielectric elastomer (DE) material
- Li et al. Self-powered soft robot in the Mariana Trench, Nature (2021) doi: 10.1038/s41586-020-03153-z

- Cai et al., "Research on Robotic Fish Propelled by Oscillating Pectoral Fins", Robot Fish, 2015 ISBN:978-3-662-46870-8
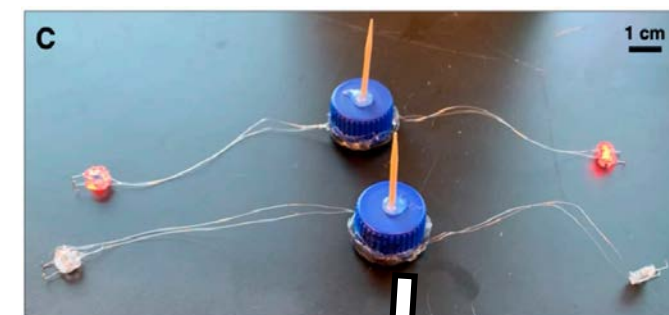
Acceleration reaction
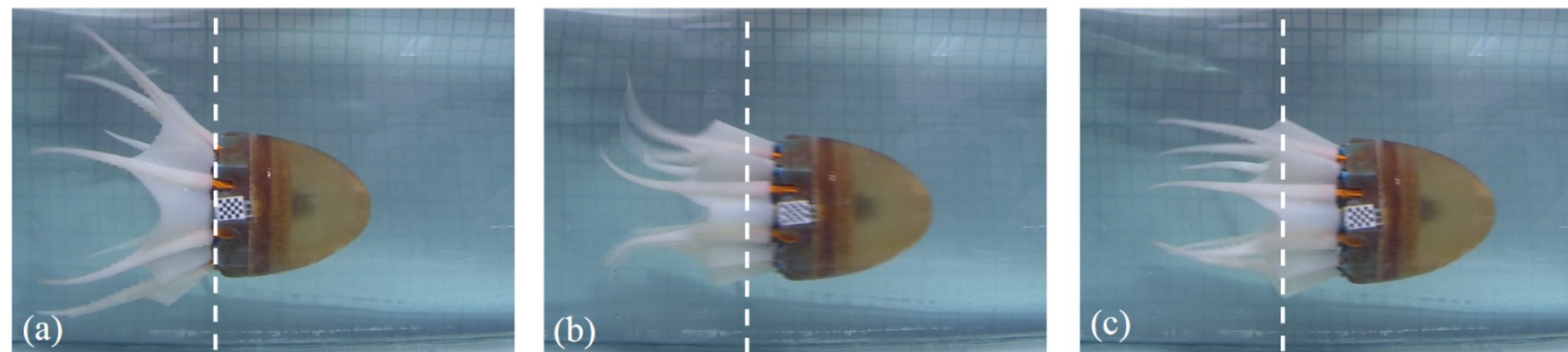
Soft, compliant web made of silicone
Sfakiotakis et al. (2014) doi:10.1109/IROS.2014.6942576
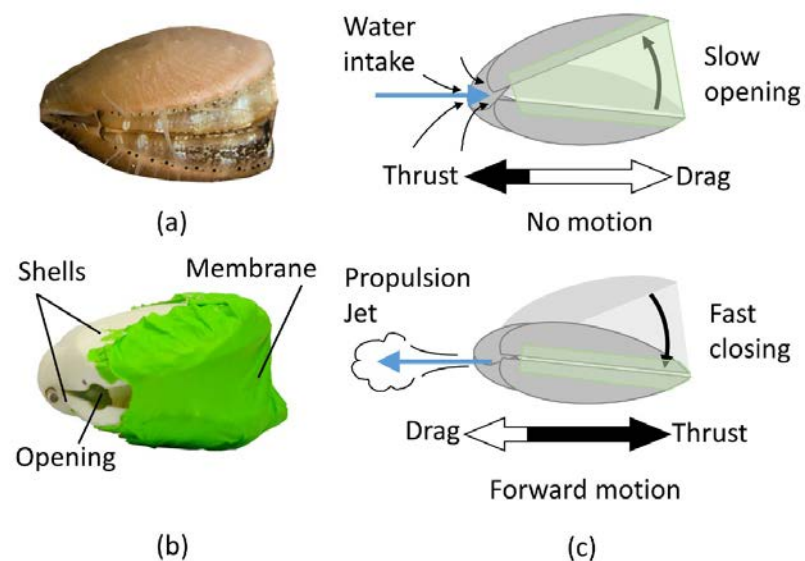
- "RoboScallop"
- Powered by a single DC motor
- Robertson et al. (2019) doi:10.1109/LRA.2019.2897144
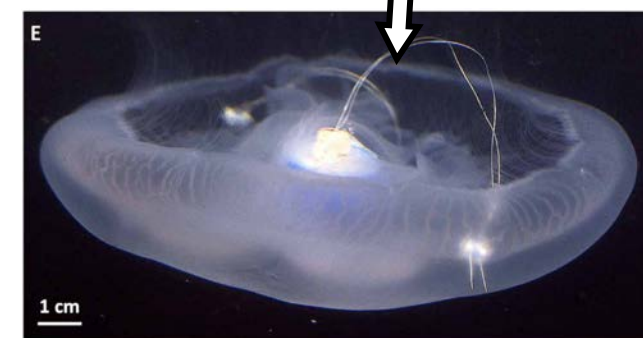
Low-power microelectronics embedded in live jellyfish enhance propulsion
(Xu, …, **Dabiri** (2020) doi:10.3390/biomimetics5040064)
(Xu & **Dabiri** (2020) doi:10.1126/sciadv.aaz3194

Pressure drag

- Turtle-inspired robot using soft material flippers change shape into legs
- Rebecca Kramer-Bottiglio (Yale University), Frank Fish (West Chester University), Simon Freeman (NUWC) (https://www.youtube.com/watch?v=Q9FyaRtLOys)
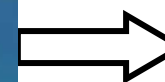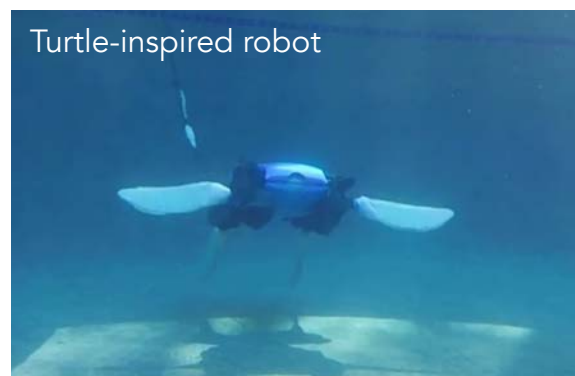
Amphibious Systems: Land & Sea-Based Missions
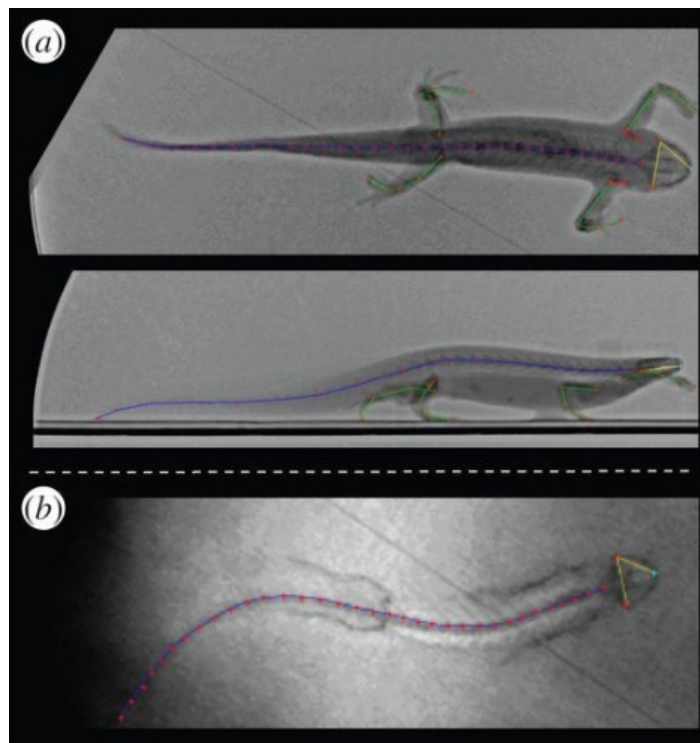
"Pleurobot": salamander-like robot
Karakasiliotis, Thandiackal, et al. (2016), From cineradiography to biorobots: an approach for designing robots to emulate and study animal locomotion, Royal Society Interface doi:10.1098/rsif.2015.1089
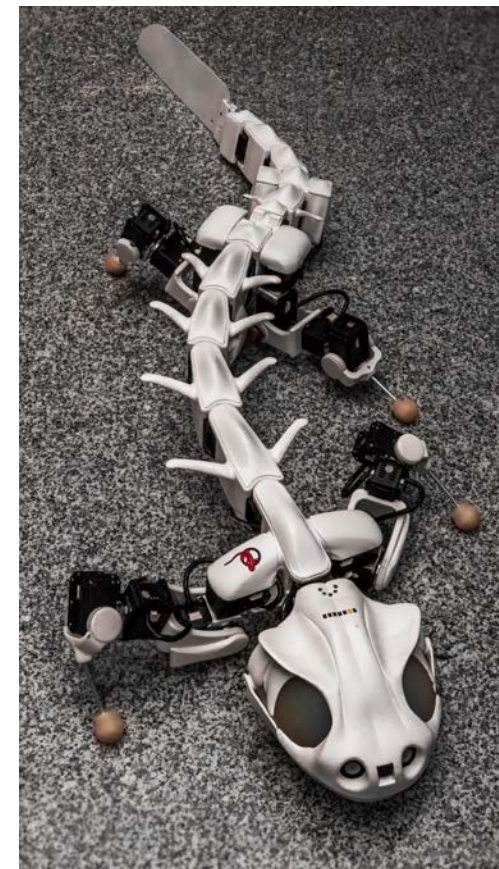

Turtle-inspired robot

Speed and Cost of Transport: Literature Review

Reference	Description	Speed (m/s)	Body Length, BL (m)	Speed (BL/s)	Actuation Frequency (Hz)	Power (W)	Work per Meter (J/m)	Mass (kg)	COT (J/kg/m)
Berlinger er al. (2021)	Finbot	0.122	0.160	0.763	4.25	3.3	27	0.15	180
Bujard et al. (2021)	Robotic squid	0.26	0.266	0.98	9.0	0.09	0.4	0.380	0.93
Chen et al. (2015)	IPMC robotic cownose ray	0.007	0.21	0.034	0.157	2.0	280	0.119	2354
Chen et al. (2021)	Leaping fish bot	1.88	0.264	7.12	15.04	89	47	0.350	135
Christianson et al. (2018)	DEA robotic leptocephali	0.0019	0.22	0.0086	0.33	0.020	10.5	0.0251	419
Christianson et al. (2019)	DEA robotic jellyfish	0.0032	0.163	0.020	0.2	0.25	78	0.23	340
Cianchetti et al. (2015)	OCTOPUS	0.05	0.17	0.3	0.75	2.6	53	3.0	18
Erturk (2015)	MFC piezoelectric fish	0.075	0.243	0.31	5.0	1.4	19	n/a	n/a
Fujiwara & Yamaguchi (2017)	Single-motor-actuated fish	0.58	0.345	1.7	16.0	20.4	35	0.597	59.0
Kumph (2000)	Robopike	0.09	0.82	0.1	1.0	8.5	94	n/a	n/a
Kwak & Bae (2017)	Robotic water beetle	0.117	0.095	1.2	1.3	0.66	5.7	0.02265	250
Li et al. (2017)	Electro-ionic robotic fish	0.135	0.093	1.5	5.0	0.024	0.18	0.0425	4.18
Liu & Curet (2018)	KnifeBot	0.325	0.462	0.703	3.0	2.55	7.85	n/a	n/a
Long Jr. et al. (2006)	Madeleine	0.74	0.78	0.95	6.0	58.3	79	24.4	3.2
Mazlan (2015)	Robosalmon	0.143	0.90	0.16	1.0	5.4	37.8	4.30	8.8
Paschal et al. (2017)	Reconfigurable armed robot	0.1	0.6	0.2	2.0	4.51	45	2.1	21
Pham et al. (2019)	Pectoral fin-propelled robot	0.231	0.4	0.58	0.75	0.102	0.44	1.059	0.42
Sfakiotakis et al. (2015)	Robotic octopus	0.0986	0.38	0.26	0.9	3.83	38.8	2.68	14.5
Shintake et al. (2018)	DEA robotic fish	0.0372	0.15	0.25	0.75	0.92	25	0.0044	5621
Shintake et al. (2020)	Tensegrity trout robot	0.23	0.400	0.58	3.0	1.9	8.3	0.102	81.0
Villanueva et al. (2011)	Robojelly	0.0542	0.6	0.1	0.5	17.0	314	0.242	1296
Villanueva et al. (2013)	Cyro	0.0847	0.316	0.268	0.12	70.0	826	76.0	11
Wang et al. (2010)	SPC-3 UUV	1.87	1.6	1.2	2.5	194.0	104	n/a	n/a
Wang et al. (2021)	Robotic larval zebrafish	0.133	0.0043	31	83	4.8E-05	3.6E-04	1.535E-06	235
White et al. (2020)	Tunabot Flex	1.17	0.255	4.60	8.0	4.10	3.50	0.190	18.4
White (2022)	Tunabot Prototype	0.64	0.4064	1.6	8.0	10.8	16.9	0.90	18.8
Yu et al. (2016a)	Single-motor-actuated fish	1.14	0.37	3.1	8.0	25.6	22.5	n/a	n/a
Zhong et al. (2017)	Wire-driven robotic fish	0.67	0.31	2.2	3.0	5.6	8.3	0.5	17
Zhu et al. (2019)	Tunabot	1.02	0.255	4.00	14.8	8.67	8.50	0.306	27.8

Why am I here?

Using biology to inspire new solution pathways for fast, efficient underwater robots
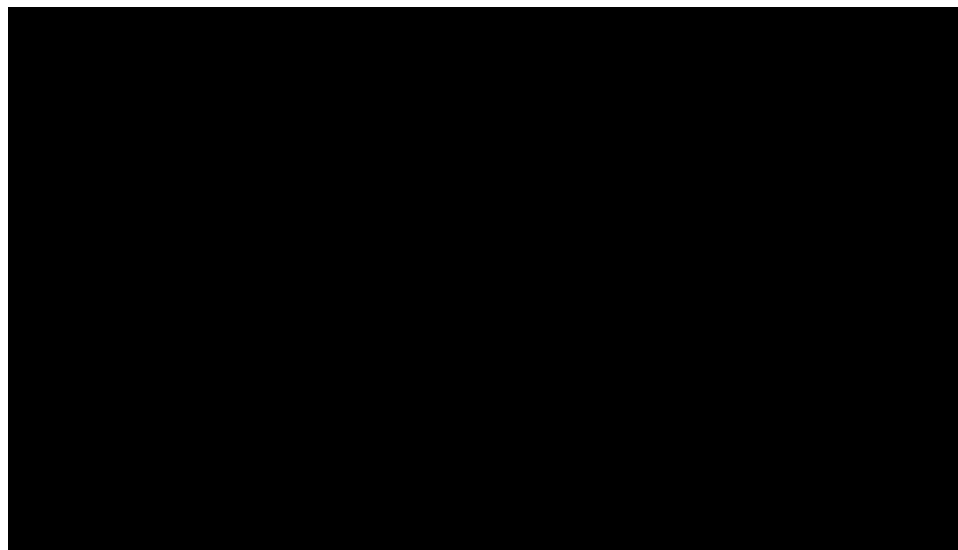
Towards a Mission-Configurable Stealth Underwater Batoid

ONR MURI
Program Manager:
Dr R. Brizzolara
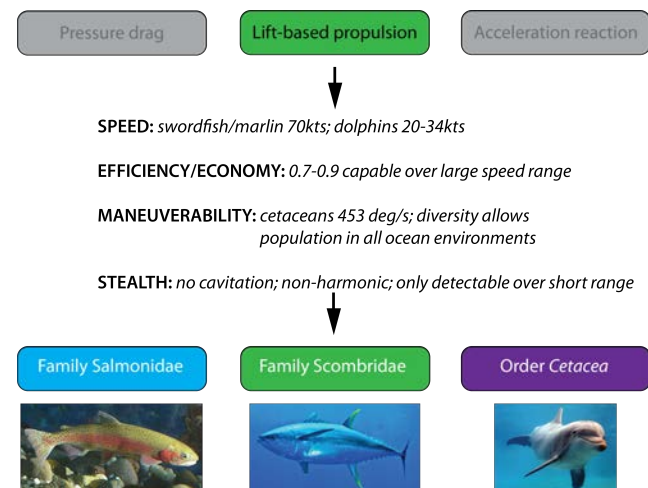
Bio-inspired flexible propulsors for fast, efficient swimming: What physics are we missing?

ONR MURI
Program Manager:
Dr R. Brizzolara

UVA Tunabot

UNIVERSITY of VIRGINIA   HARVARD UNIVERSITY   PRINCETON UNIVERSITY   LEHIGH UNIVERSITY

TUNABOT

High Speed <u>And</u> High Efficiency

Pressure drag   Lift-based propulsion   Acceleration reaction

SPEED: *swordfish/marlin 70kts; dolphins 20-34kts*

EFFICIENCY/ECONOMY: *0.7-0.9 capable over large speed range*

MANEUVERABILITY: *cetaceans 453 deg/s; diversity allows population in all ocean environments*

STEALTH: *no cavitation; non-harmonic; only detectable over short range*

Family Salmonidae   Family Scombridae   Order *Cetacea*

Tuna: biology and anatomy

- Atlantic Bluefin tunas migrate across oceans

- Eastern and western populations mix for feeding but not breeding

- Spawn in Mediterranean and gulf of mexico

- Bluefin grow large (over 1000 lbs) and can sometimes sell for over $1.5 milion per fish.

Figure 1
At Least 2 Populations of Atlantic Bluefin Tuna: Highly Migratory and Highly Mixed
Western and eastern bluefin mix to feed but separate to breed

Tuna: biology and anatomy
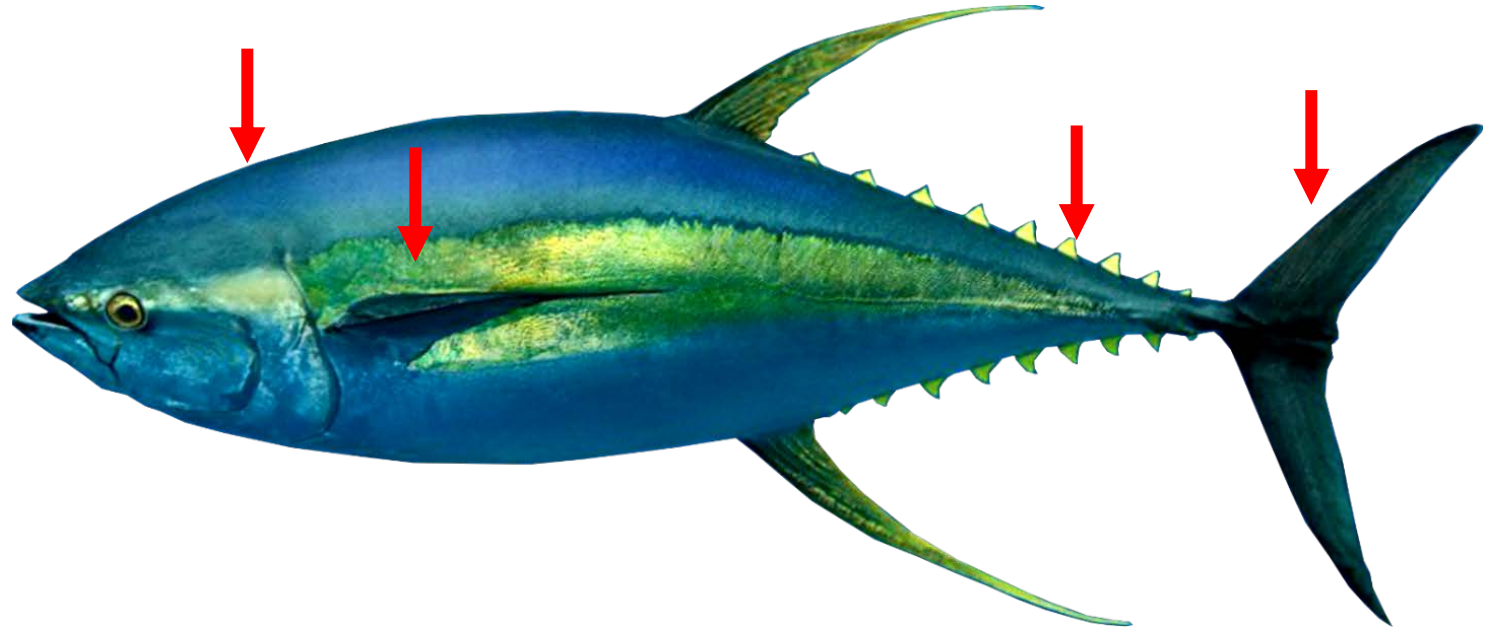
- Key features of tuna:
  - streamlined shape
  - lunate high-aspect ratio tail
  - wing-like pectoral fins
  - finlets
  - caudal peduncle and keel

Research Objectives

1. Study <u>high-performance</u> fish swimming using bio-inspired research platforms
   - Yellowfin tuna (Thunnus albacares)

High speed: High efficiency:
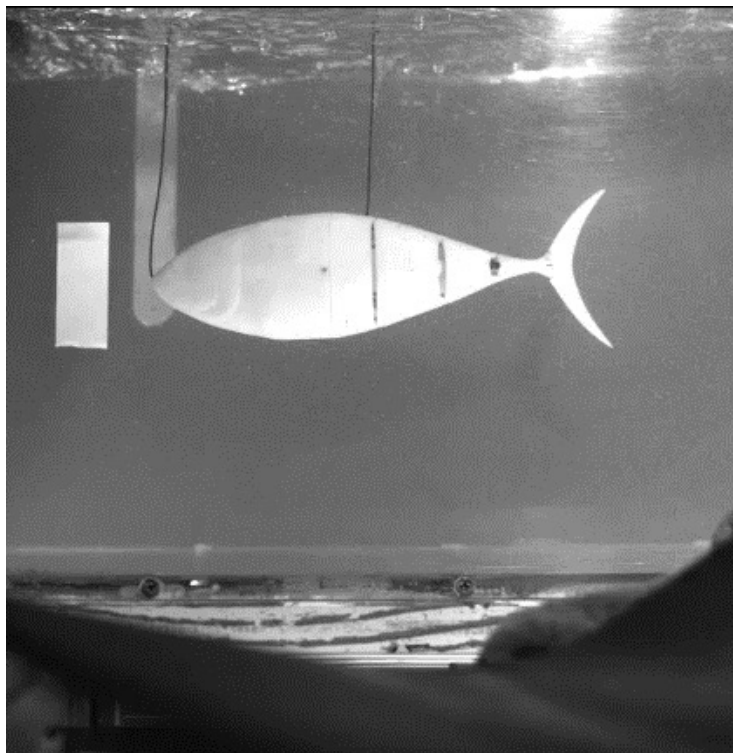Body Lengths per second (BL/s)   Cost of Transport (J/kg/m) $COT = \dfrac{Power}{Mass \cdot Speed}$

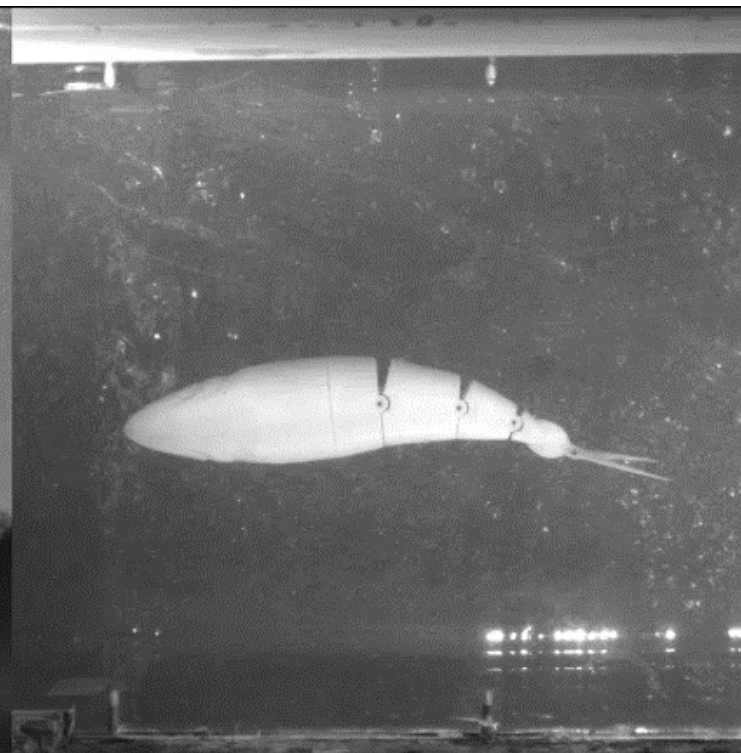2. <u>Close</u> the performance gap between biology and robotic systems

Tunabot Flex Swimming Performance

MARINE CARBON SENSING WORKSHOP
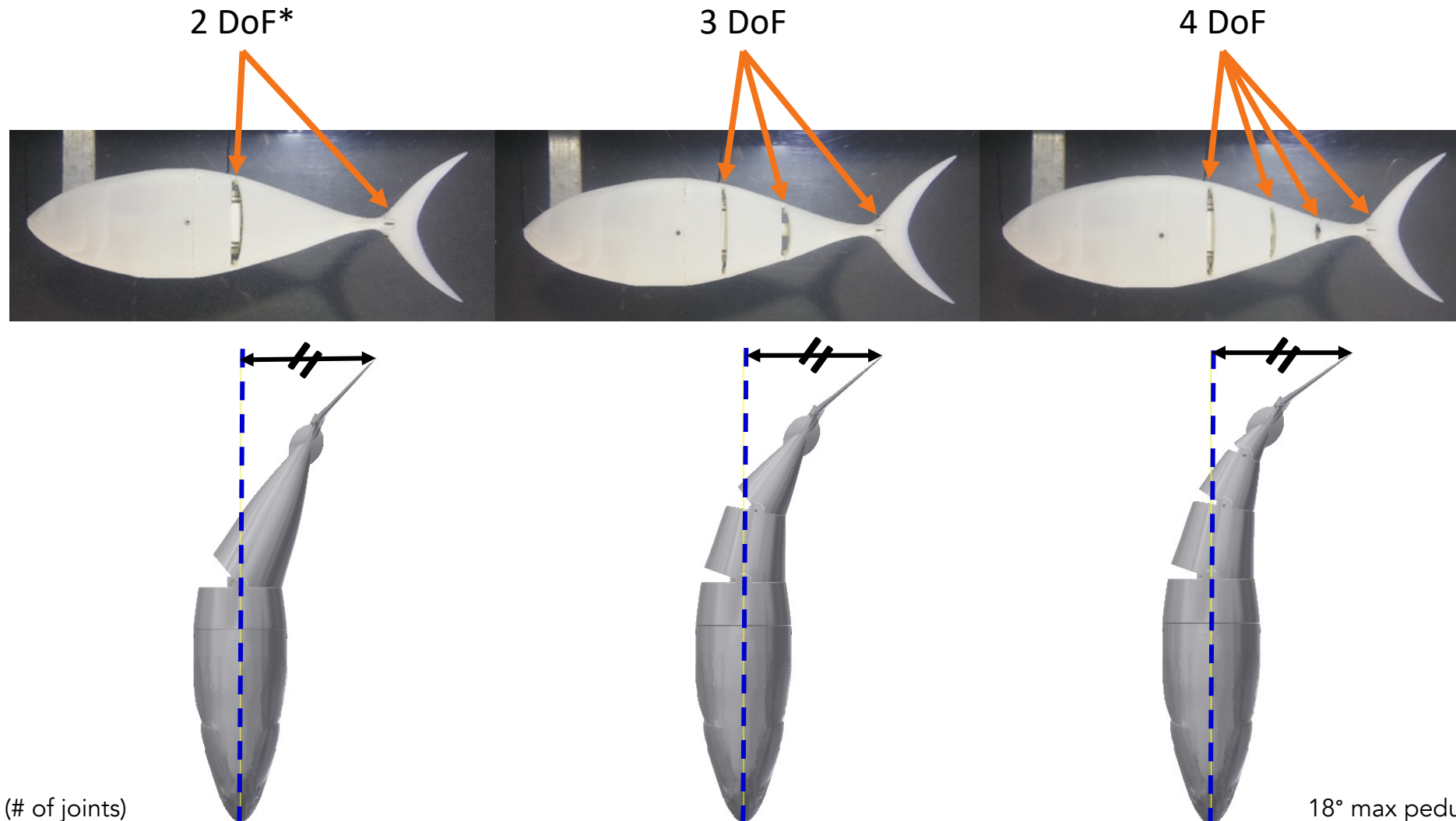
Lateral View

Ventral View

Lauder Lab flow tank, 4.6 BL/s, 8.0 Hz, 0.57x playback speed

Performance Space
Speed & Frequency

Performance Space
Speed & Frequency

Leaping robotic dolphin
Yu et al. (2016)
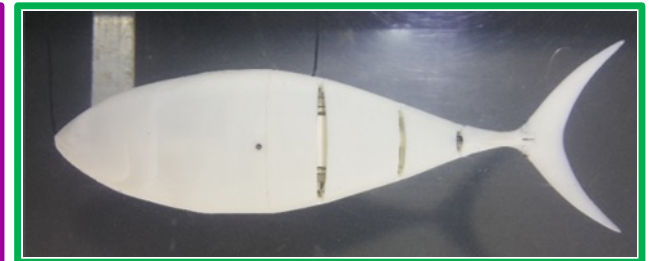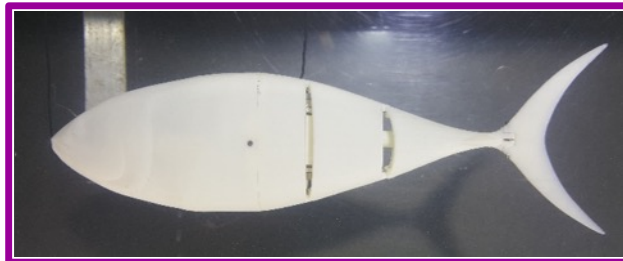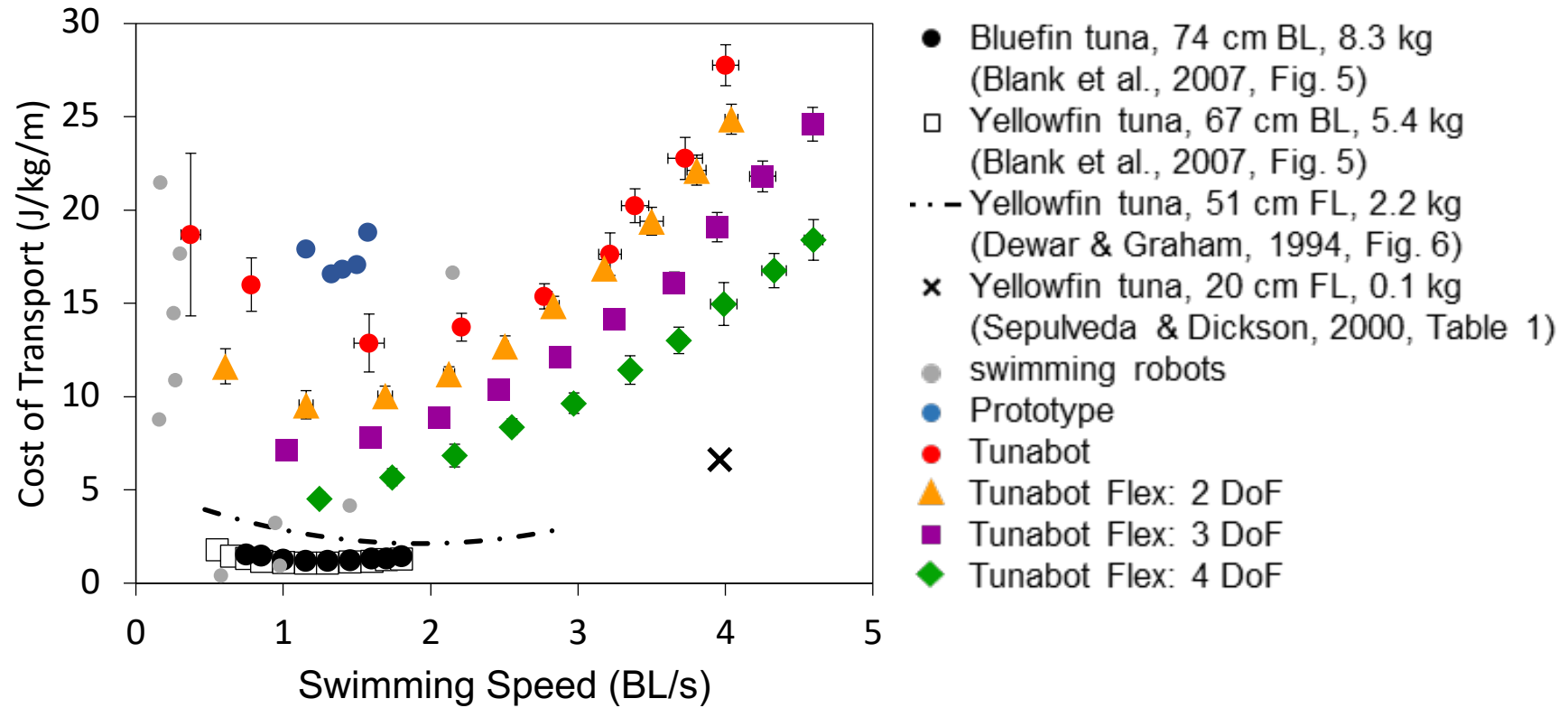Yu et al. (2019)

Professor
Junzhi Yu
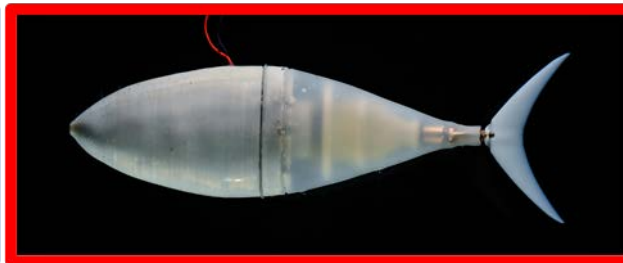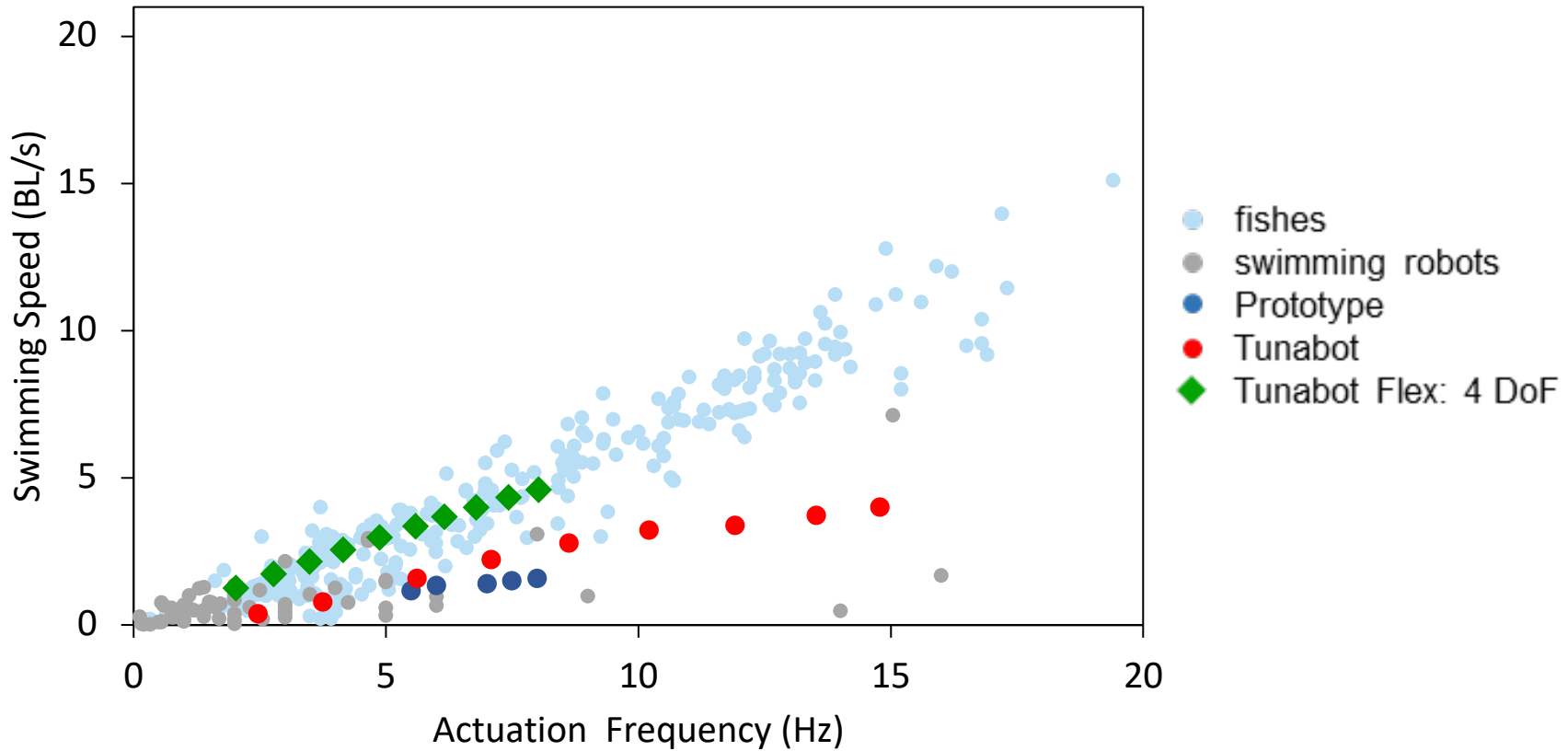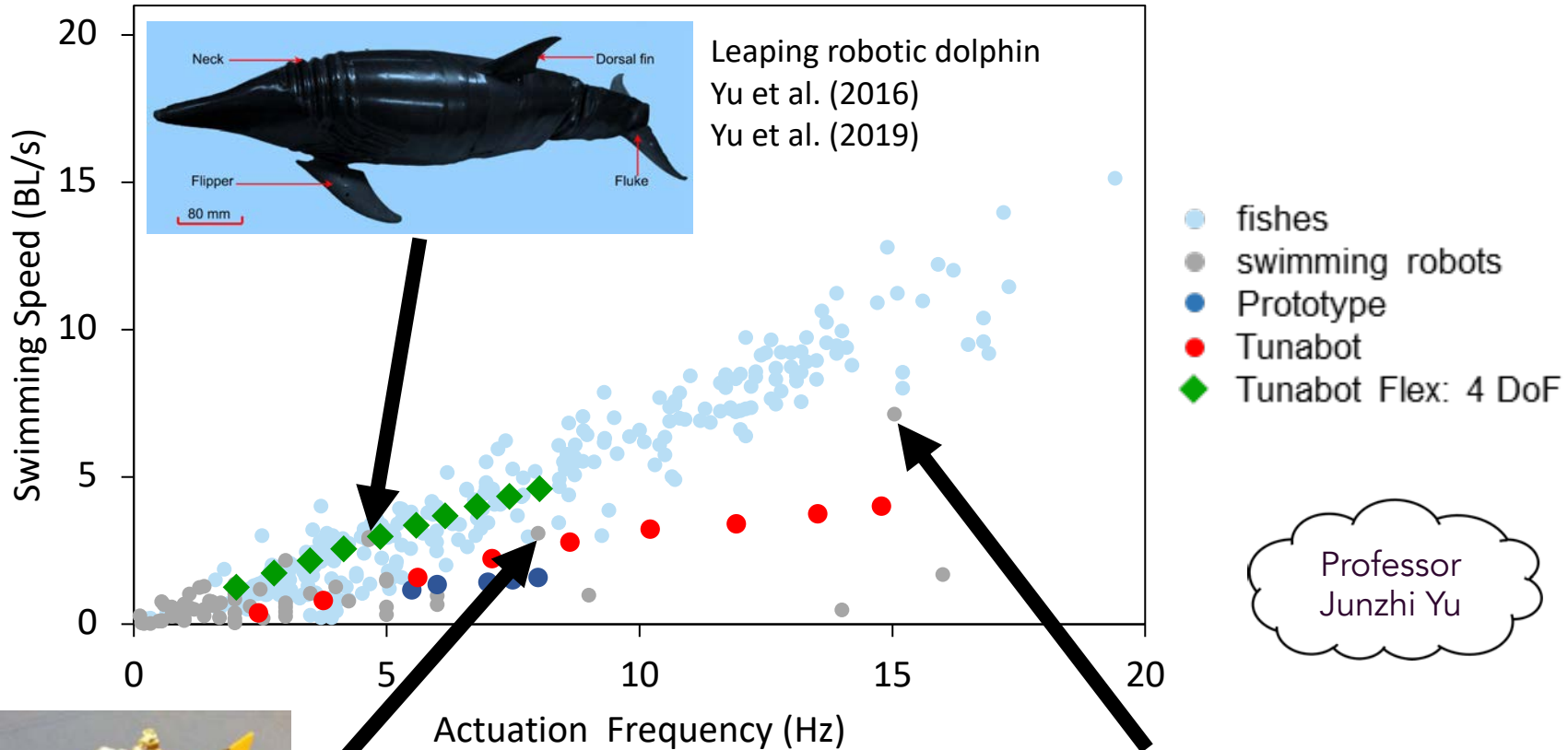
Single-motor-actuated fish
Yu et al. (2016)

Leaping fish bot
Chen et al. (2021)

Performance Space
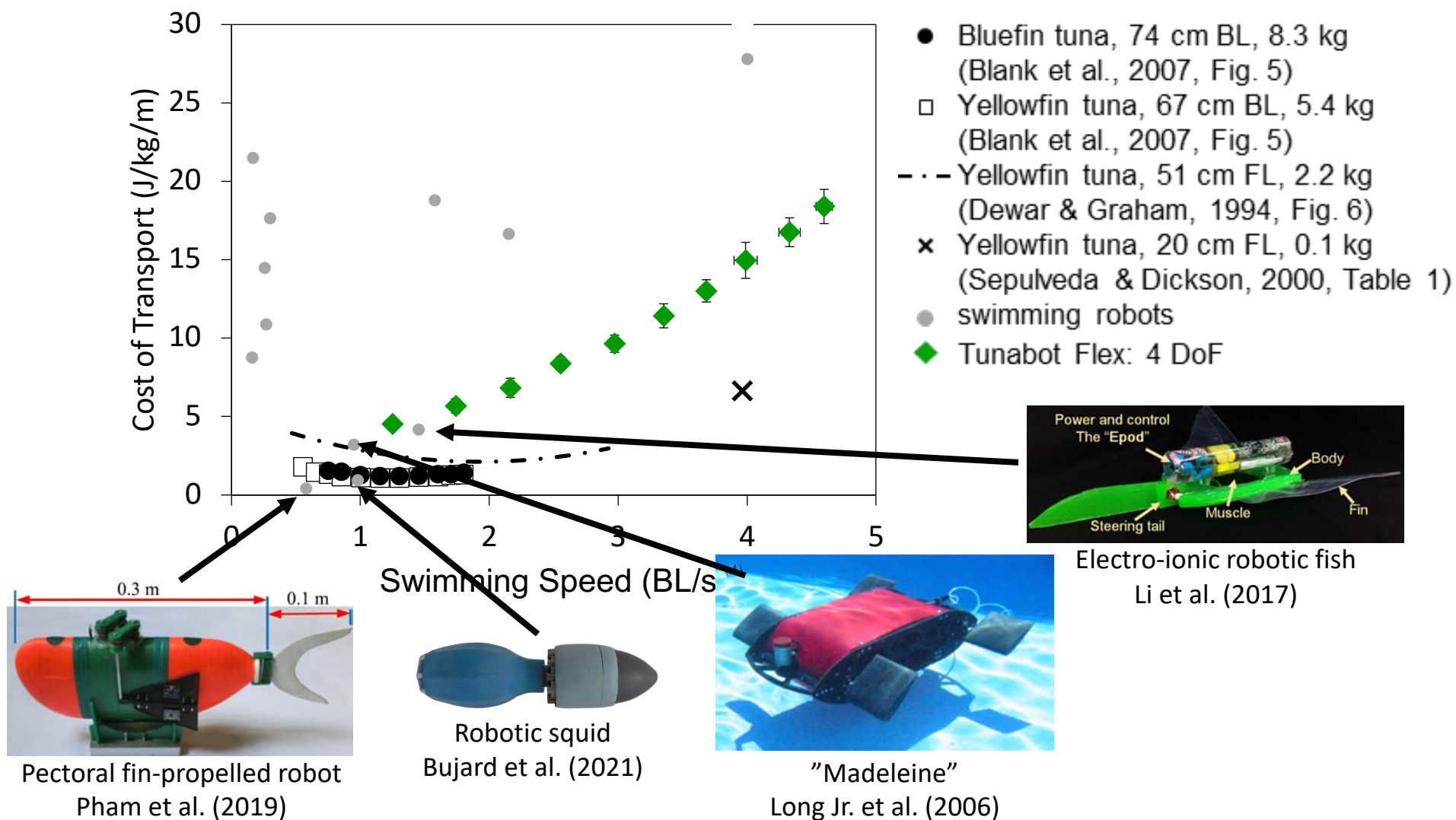# Cost of Transport
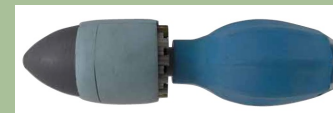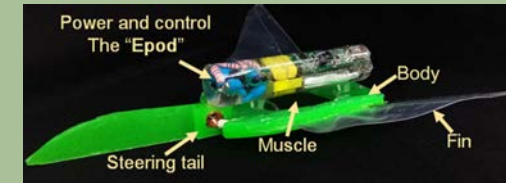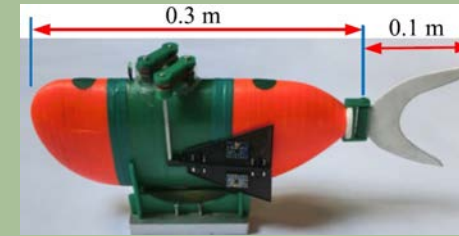
Performance Space
Cost of Transport

Legend:
- ● Bluefin tuna, 74 cm BL, 8.3 kg (Blank et al., 2007, Fig. 5)
- □ Yellowfin tuna, 67 cm BL, 5.4 kg (Blank et al., 2007, Fig. 5)
- –·– Yellowfin tuna, 51 cm FL, 2.2 kg (Dewar & Graham, 1994, Fig. 6)
- × Yellowfin tuna, 20 cm FL, 0.1 kg (Sepulveda & Dickson, 2000, Table 1)
- ● swimming robots
- ◆ Tunabot Flex: 4 DoF

Axes: Cost of Transport (J/kg/m) vs Swimming Speed (BL/s)

Power and control
The "Epod"
Body
Steering tail   Muscle   Fin

Electro-ionic robotic fish
Li et al. (2017)

0.3 m   0.1 m

Pectoral fin-propelled robot
Pham et al. (2019)

Robotic squid
Bujard et al. (2021)

"Madeleine"
Long Jr. et al. (2006)

State of the Field
High Speed AND High Efficiency

High Speed

Low Cost of Transport

Fish Schooling

- Simultaneously surveying more area, more intelligently
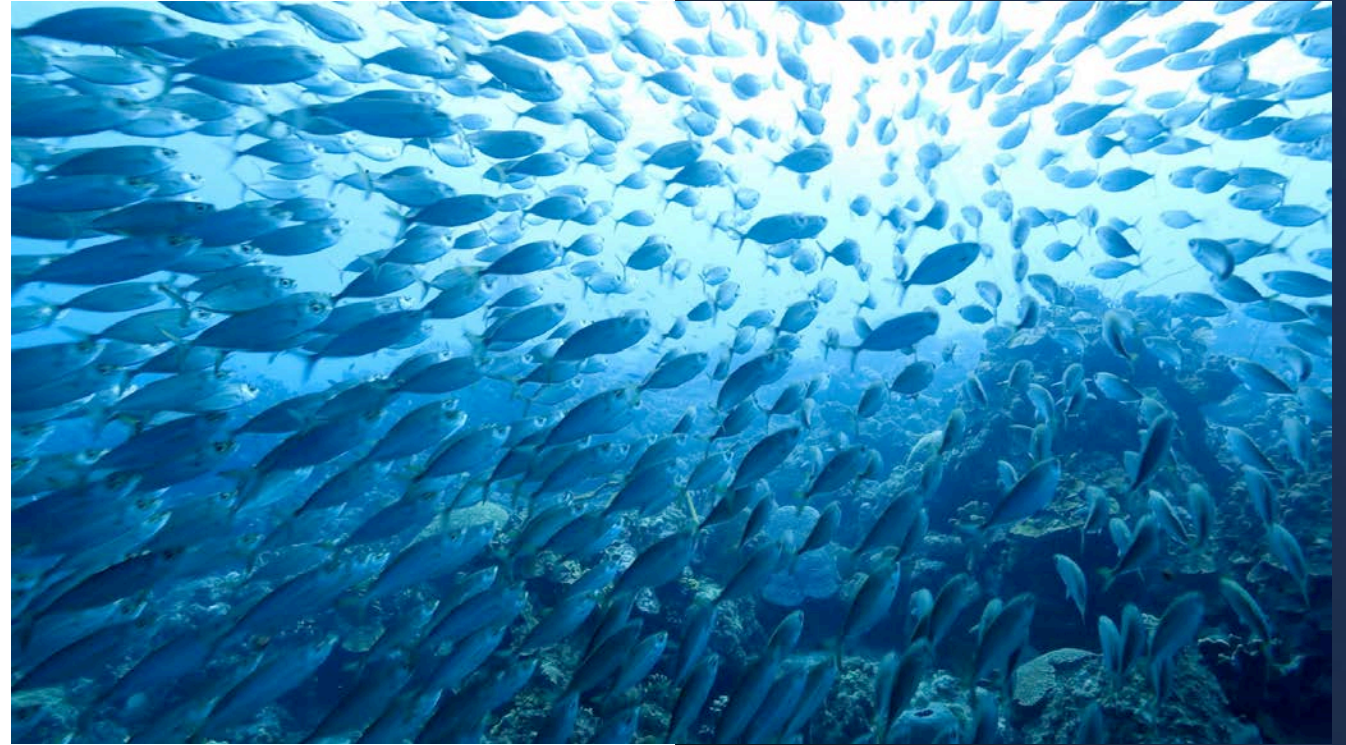
Revealing the Hydrodynamic Principles of Three-Dimensional Fish Schools: From Biology to Schooling Robotics

Principal Investigator
Keith Moored, Lehigh University, kmoored@lehigh.edu
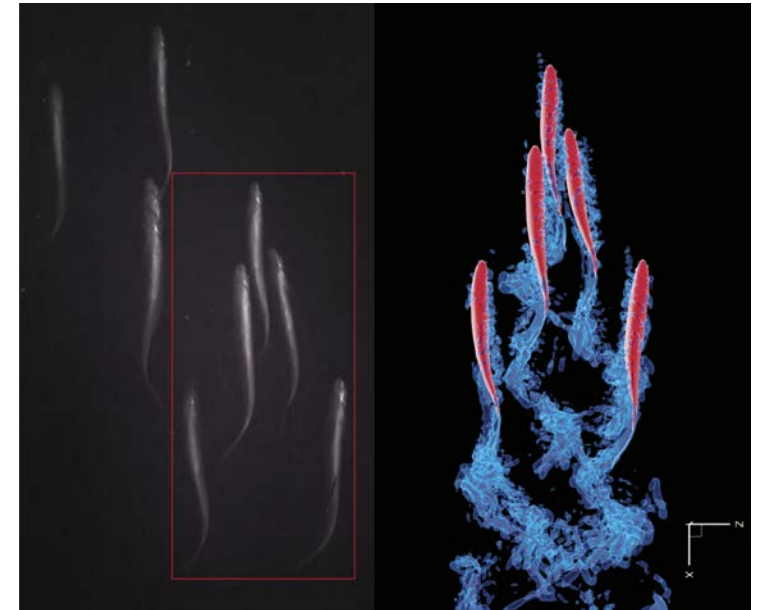
Co-Principal Investigators
George Lauder, Harvard University
Radhika Nagpal, Princeton University
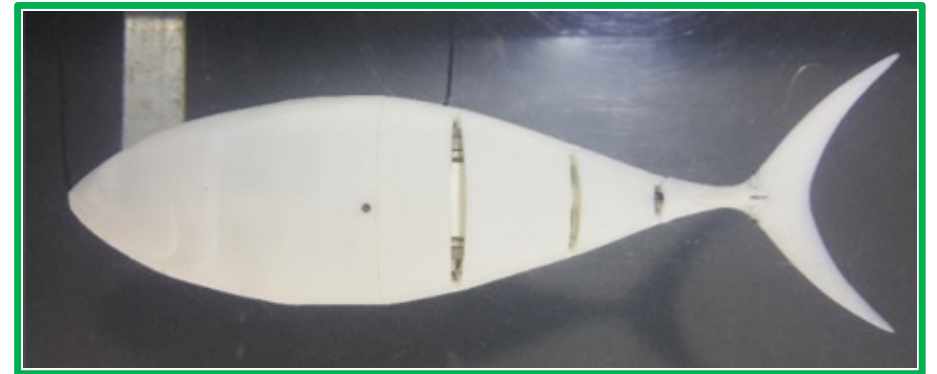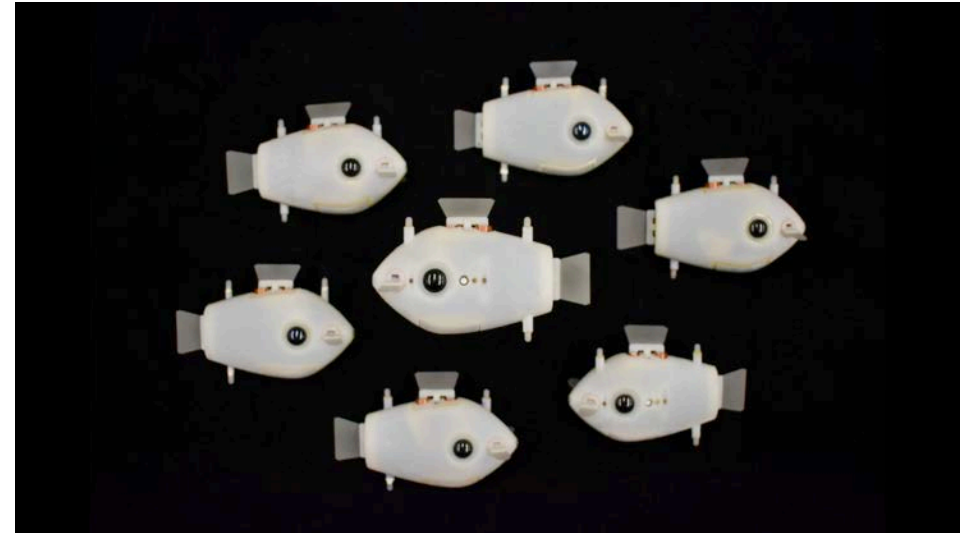Hilary Bart-Smith, University of Virginia
Daniel Quinn, University of Virginia
Haibo Dong, University of Virginia

BlueSwarm: bio-robots with decentralized schooling control

- Fish-inspired robot swarm

- Variable collective behaviors depending on mission requirements

- Berlinger et al. (2021) doi:10.1126/scirobotics.abd866

High-performance + schooling control

FINAL THOUGHTS

- **This is a challenging problem and exciting: lots of questions**
  - Can current technologies be adapted and expanded to explore all oceanic zones?
  - Will we require new technologies and approaches?
    - Is bio-inspired a potential solution path? Soft-systems?
  - Synergies between sensor development and platform and platform control development (control co-design)?
  - Energetics costs?
    - Platform range
    - Recharging implications (Charging stations? On-board power generation?)
  - Economics?